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Eidgenössisches Departement des Innern EDI
Bundesamt für Meteorologie und Klimatologie MeteoSchweiz

A Python Dynamical Core for Operational Numerical Weather Prediction

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MeteoSwiss and the EXCLAIM team

[1]MeteoSwiss, [2]CSCS

Current Operational Numerical Weather Prediction at MeteoSwiss

ICON

The ICON modeling framework

- Open-source framework for weather, climate, and environmental prediction
- Designed to be flexible, scalable, and high-performance
- Advances our understanding of the Earth's climate system

The ICON partnership

- Represents a close and diverse collaboration between its members and development partners
- Integrates research and operational expertise in weather and climate
- Combines high-performance computing and data handling

DKRZ DEUTSCHES KLIMARECHENZENTRUM

MAX-PLANCK-INSTITUT FÜR METEOROLOGIE

Deutscher Wetterdienst Wetter und Klima aus einer Hand DWD

C2SM Center for Climate Systems Modeling

KIT Karlsruher Institut für Technologie

The ICON Software

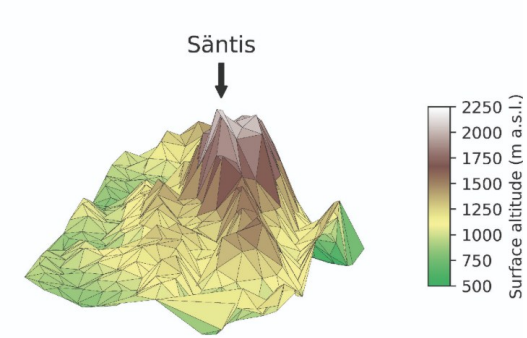
- Written in low-level Fortran with architecture-specific optimizations (CPU, GPU, vector)
- Large code base with more than one million lines
- Current design has limited modularity, reducing ease of maintenance and extensibility

➡ Opportunity for modernization

ICON at MeteoSwiss, C2SM, and beyond

- Operational at MeteoSwiss for NWP on a GPU system since May 2024 (ICON-CH1-EPS, ICON-CH2-EPS)
- Used at ETHZ/C2SM and other Swiss institutions for weather and climate research, especially regional simulations
- Backed by a close partnership with and strong support from CSCS

ICON-CH1-EPS and ICON-CH2-EPS domain



ICON triangular grid at 1km

HPC Systeme ICON-22

- Use of HPC Services on ALPS @ CSCS
- Versatile clusters (IaC)
- Elasticity
- 2 locations: Lugano and Lausanne

Production: vCluster tasna
44 GPU nodes
- 4 x NVIDIA A100 96 GB GPUs
- 1 x AMD EPYC 7713 512 GB CPU

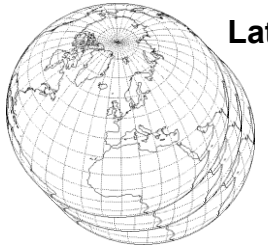
18 CPU nodes
- 2 x AMD EPYC 7713/7742 512 GB CPUs

Failover and R&D: vCluster balfrin
- 30 – 54 GPU nodes
- 18 – 24 CPU nodes

MeteoSchweiz

Forecasting System based on ICON

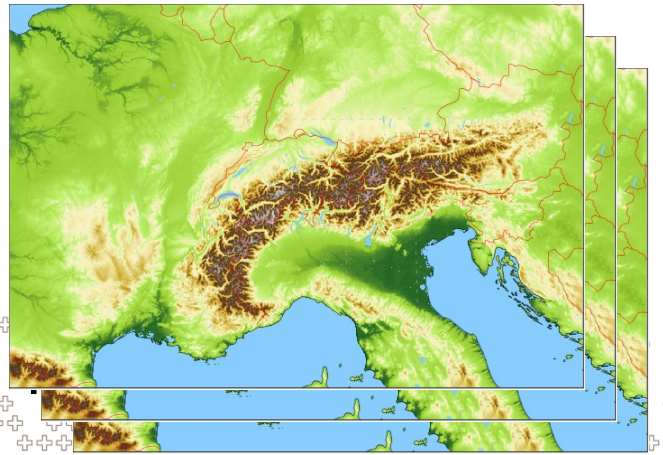
Ensemble Data Assimilation:
LETKF
40+1 members at 1.0 km grid size
with ICON-CH1 setup (SPPT)
hourly cycling



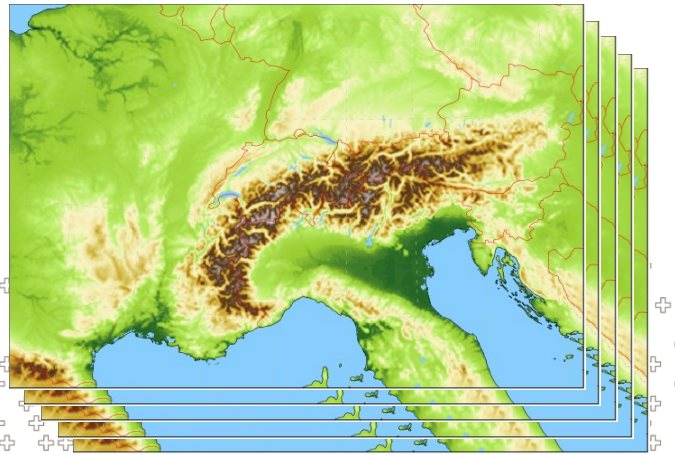
Lateral boundary conditions:
IFS ENS
9 (18) km
4x per day

operational since 28 May 2024

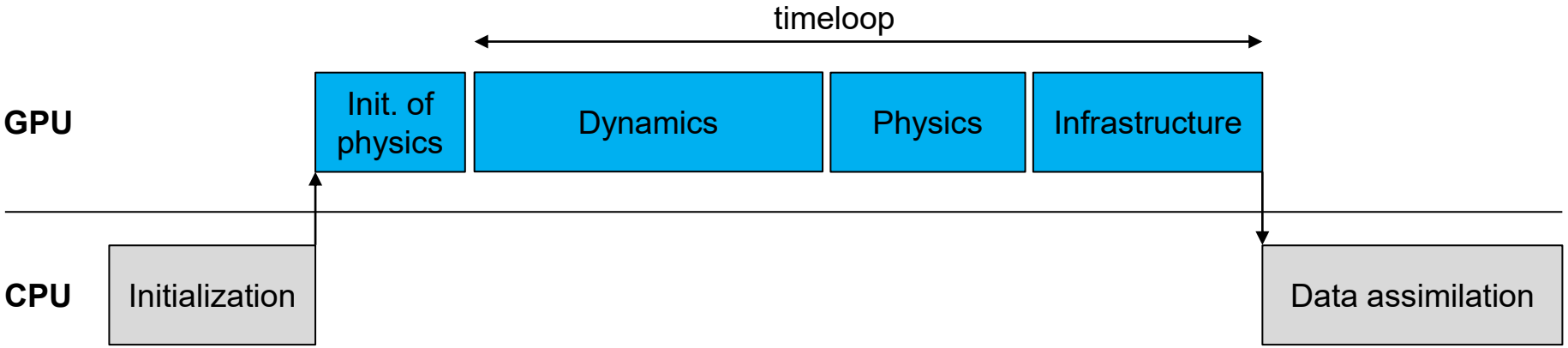
ICON-CH1-EPS: 33 hour forecasts, 8x per day
1.0 km grid size (R19B08), 80L
11 ensemble members



ICON-CH2-EPS: 5 day forecasts, 4x per day
2.1 km grid size (R19B07), 80L
21 ensemble members

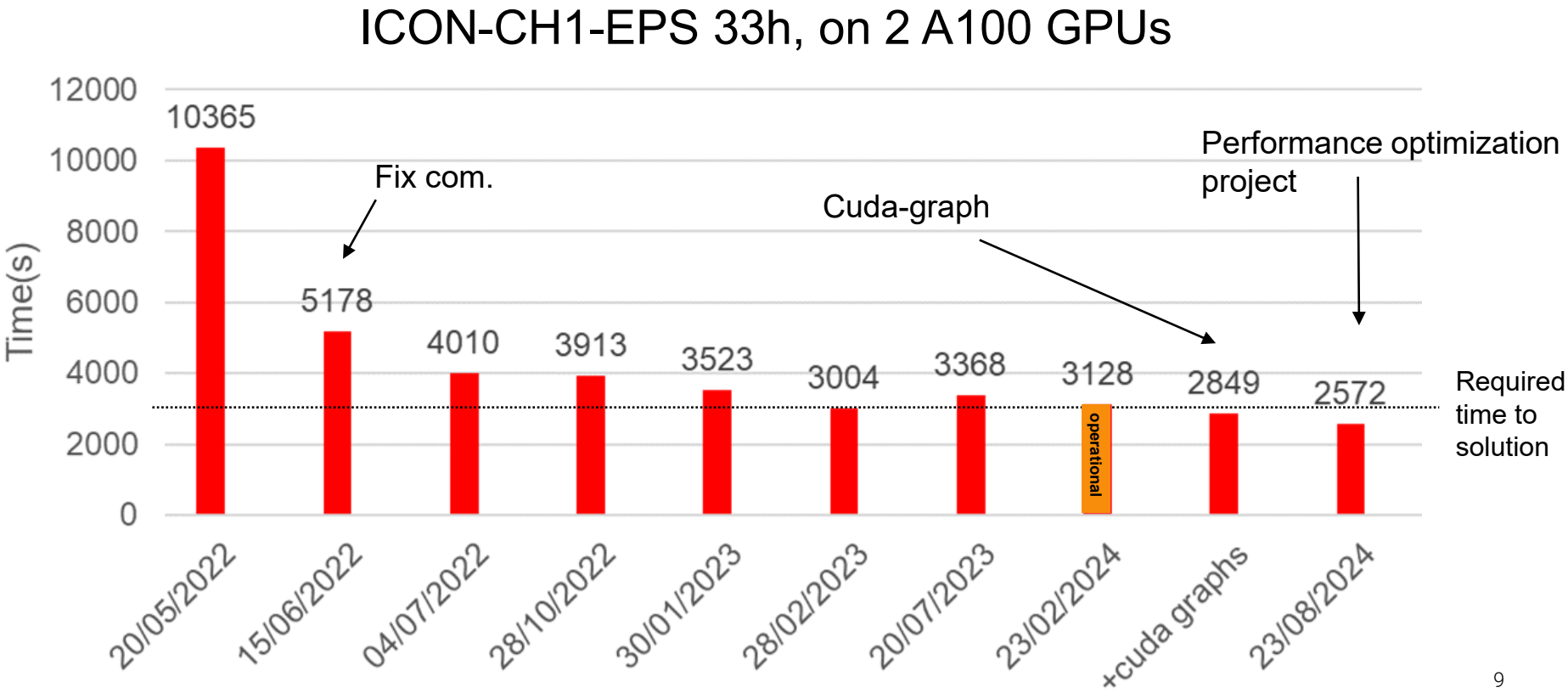


OpenACC strategy

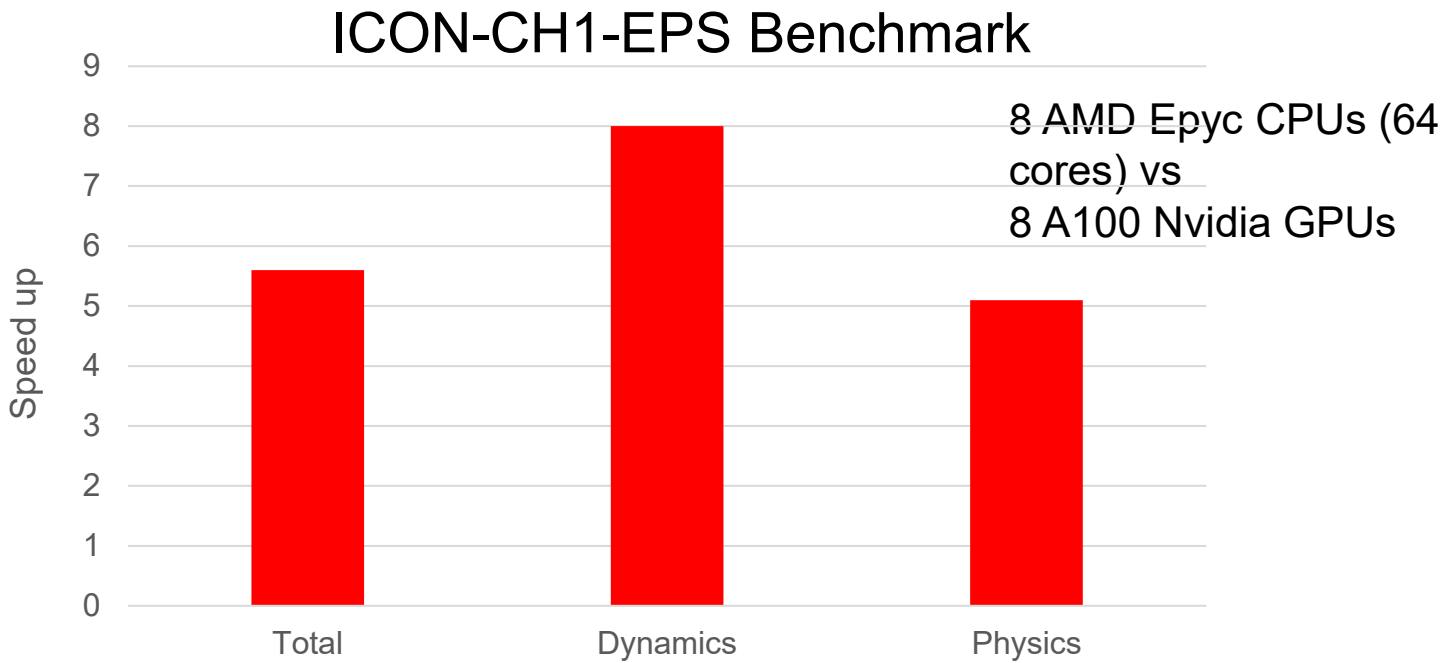


- Regular automated testing and performance monitoring (Kibana)
- Clear implementation and style guidelines
- Support for double and mixed precision

A long way to performance on GPU



CPU / GPU performance comparison



- 5.6x speed up factor when comparing CPU to GPU
- Submitted paper, pre-print: https://doi.org/10.5194/egusphere-2025-3585

Future Operational Numerical Weather Prediction at MeteoSwiss at MeteoSwiss

Who is EXCLAIM?

The Executive Team


Nicolas Gruber


Thomas Schulthess


Christoph Schär


Oliver Fuhrer


Andreas Prein

The EXCLAIM PIs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Dominik Brunner


Torsten Hoefler


Christof Appenzeller

The Core Team

The close Collaborators

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CSCS GT4Py:
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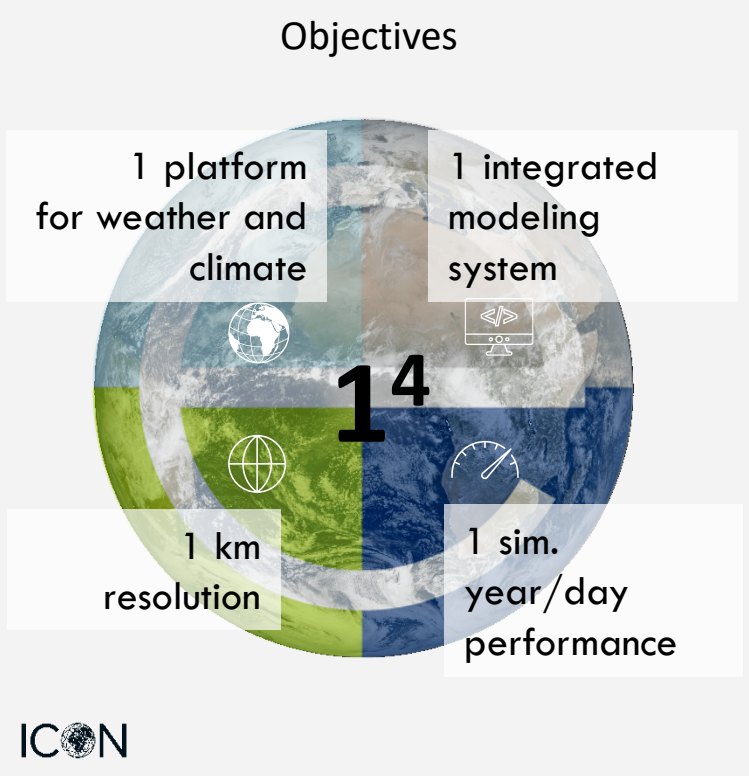
Felix Thaler

What is EXCLAIM ?

Extreme-scale computing and data platform
for cloud-resolving weather and climate modeling

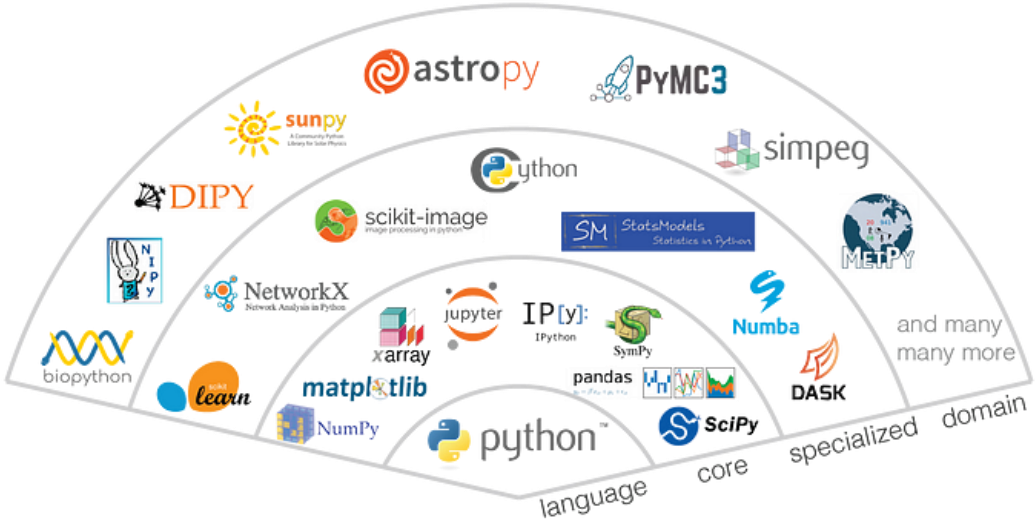
- EXCLAIM is a 6-year ETH project (2021–2027)
- Funded with 10 MCHF
- Aims to build a modern ICON infrastructure
- Targets the most challenging weather and climate simulations on modern supercomputers

➡ Modernization in Python



Why Python: Ecosystem

- Formatting / Linting
- Plotting
- Debugging
- IDE Support
- Refactoring
- Plotting
- I/O (Zarr, yaml, NetCDF)
- Arrays (NumPy, Xarray)
- …

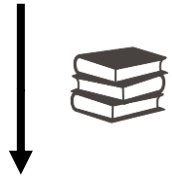


Synergy with ML

MeteoSchweiz

GT4Py Domain Specific Language (DSL)

$$\underline{\nabla}_{\underline{n}}\psi(e) = \frac{\psi(c_1(e)) - \psi(c_0(e))}{\hat{l}}$$



Modern, maintainable Python code

```
@field_operator
def _nabla(psi: Field[[EdgeDim, KDim], float],
           lhat: Field[[EdgeDim], float],
) -> Field[[EdgeDim, KDim], float]:
    return (psi(E2C(1)) - psi(E2C(0)))/lhat
```

→ **GT4Py** →

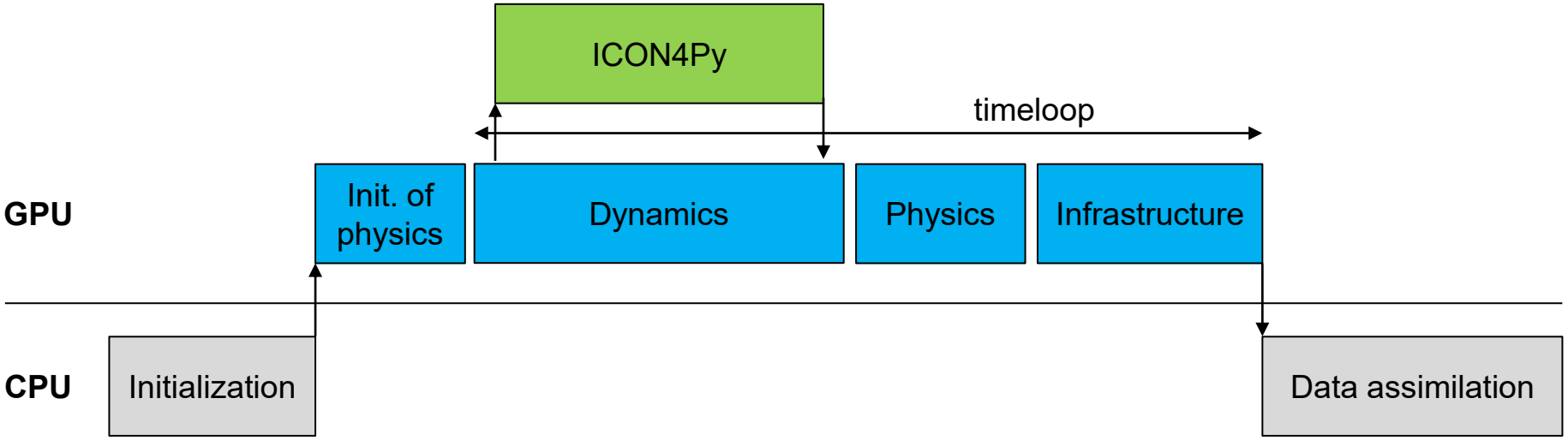
Optimized and hardware specific code

```
double _var_25[5]  DACE_ALIGN(64);
double _var_35[5]  DACE_ALIGN(64);
double _var_38[5]  DACE_ALIGN(64);
double _var_41[1]  DACE_ALIGN(64);
for (auto i_Edge_36 = 0; i_Edge_36 < _num_Edges;
    long long _i_Edge =
____stencil_arg0_i_Edge;
    const double* _inp = &__stencil_arg0[0];
    double* _out = _var_35;
…
```

Separation of concerns

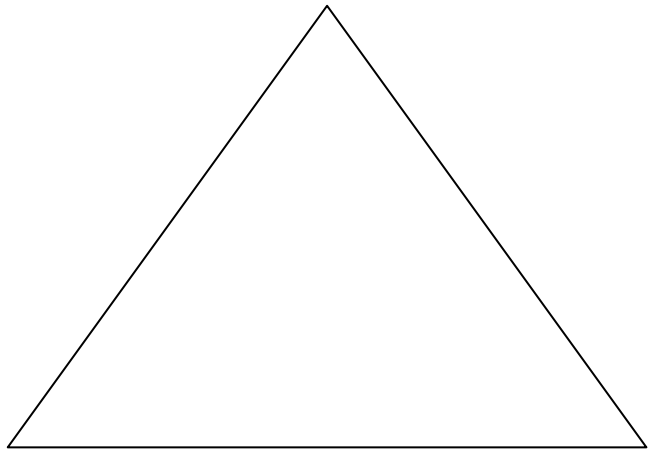
CSCS

ICON4Py strategy

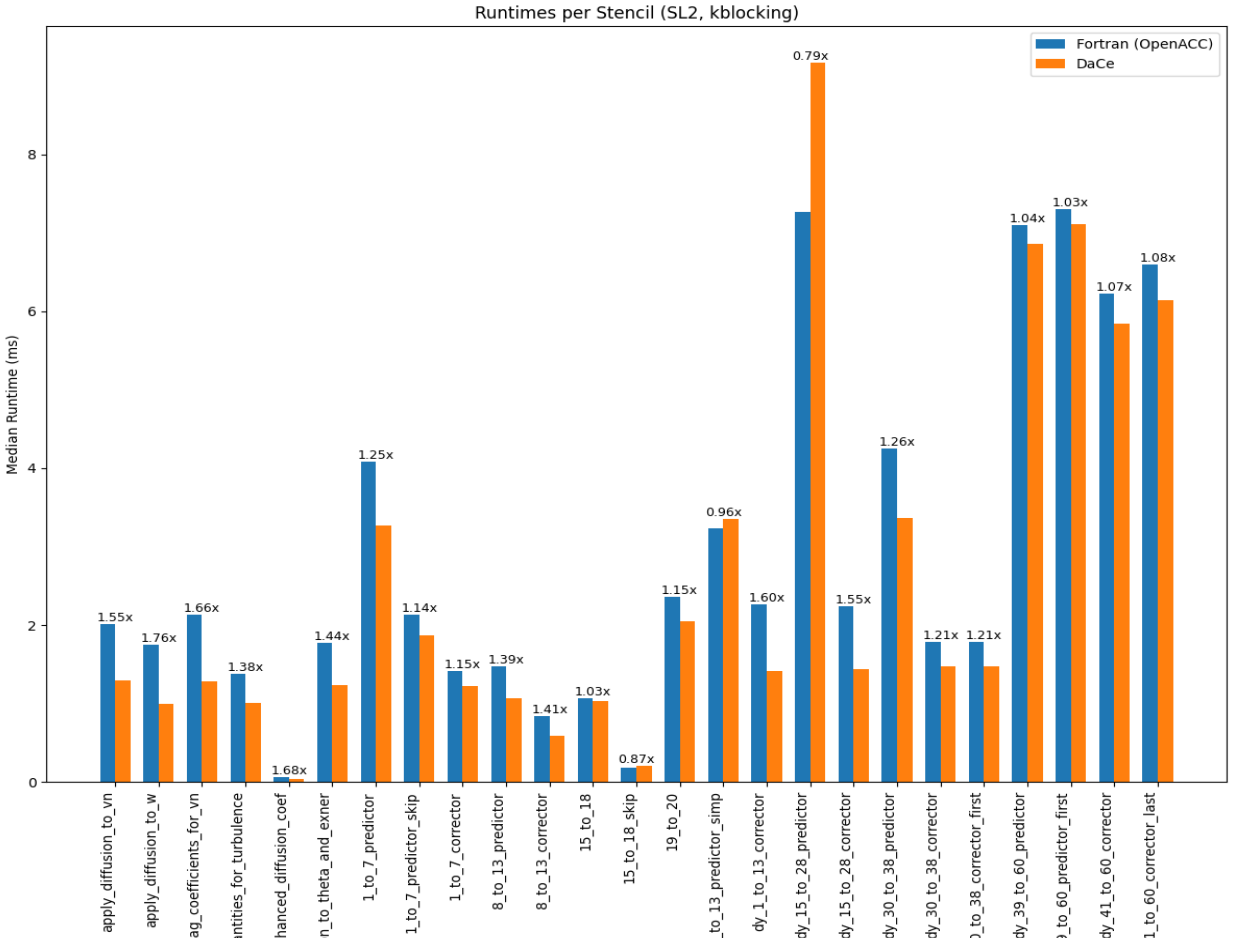


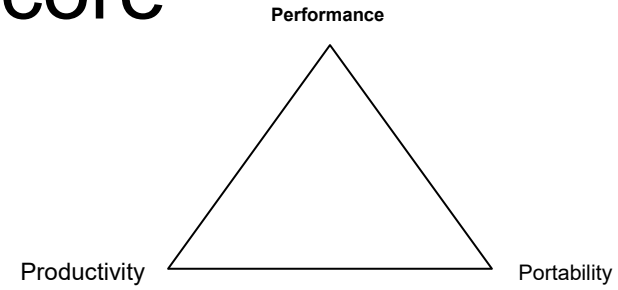
- Regular automated testing and performance monitoring (Bencher)
- Support for double and mixed precision, single precision is in progress

The 3P Challenge in Software Design



Performance ICON4Py dycore





- Achieved 4–8% performance improvement over OpenACC
- Ongoing work to get further performance improvements

EXCLAIMS achievements and next steps

- ICON4Py dycore integrated with existing Fortran code
- ICON4Py dycore under validation and optimization targeting 1.2× speedup
- Planned for MeteoSwiss operations once requirements are met
- Provides a platform for high-resolution climate simulations and data
- Long-term goal: full Python prototype of ICON for selected climate application

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